Greenhouse gas reporting for biofuels: A comparison between the RED, RTFO and PAS2050 methodologies

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Abstract

Biofuels have been identified as a potential short-term solution for reducing greenhouse gas (GHG) emissions from road transport. Currently, '1st generation' biofuels are produced from food crops, but there are concerns with the indirect effects of utilising edible crops for fuel. There is increased interest in producing '2nd generation' biofuels from woody crops and straw, as these can be grown on lower grade land or do not compete directly with food. In order to ensure that biofuels actually deliver emission savings, the overall GHG balance of producing them must be calculated accurately, and compared with conventional fossil fuels. The GHG balance can vary significantly however, depending on biomass type, the production processes, the indirect effects, and also by the method by which the GHG emission balance is calculated. Currently, in the UK, there are three main GHG methodologies that potentially affect biofuel producers. Each has a different approach to measuring GHG emissions from biofuel production, and each provides a different result, causing difficulties for policy makers. This study performs a partial life cycle assessment for bioethanol production from wheat grain and wheat straw to demonstrate the variability of the results between methodologies.

Keywords: Biofuels; Allocation; Greenhouse gas, Life Cycle Assessment Methodology.

1. Introduction

Concerns over world-wide climate change and our dependence on declining fossil fuel stocks has prompted interest in biofuels, especially over the last decade. There is a need to reduce greenhouse gas (GHG) emissions from road transport, as they represent 25% of UK emissions (DECC 2010), and this is expected to grow due to increased car ownership and congestion (BERR 2006). This has promoted the development of lower carbon options, with stricter emission standards for new vehicles, as well as hybrid and electric vehicles. It has been estimated that a complete replacement of the vehicle fleet would require up to 16 years (WRAP 2002), during which we may see alternative sustainable sources become available, such as hydrogen fuel cell technology (RS 2008). It has been suggested that biofuels offer a short-term solution to reducing both demand for liquid fossil fuels and emissions from the transportation sector. They can be used, at certain blends, in current car models, and a distribution network of liquid fuels already exists (RS 2008). In order to ensure that GHG emissions are actually reduced however, it is vital that the GHG balance of producing and delivering biofuels is favourable (Black et al. 2011). In literature, the life cycle assessment (LCA) of biofuels has received much attention, with concerns raised about their overall GHG balance, their effect on food prices and land use change (Searchinger et al. 2008).

1.1. 'First' and 'Second' Generation Biofuels

Currently in the UK, biofuels are produced from food crops including wheat, sugar beet and oilseed rape, with a few projects utilising waste vegetable oil. These are typically referred to as 'first generation' biofuels. There are concerns that a major switch to biofuels from food crops will lead to competition between food and fuel, and increase the pressure on land availability (RS 2008). This may lead to areas of high carbon stock and biodiversity being converted to arable land (Searchinger et al. 2008). It is suggested that future biofuels produced from non-food crops can avoid these indirect impacts by being more broadly sourced from a range of 'readily available resources' (Singh et al. 2010). Waste from food production, or biomass grown on land of low agricultural value will not compete directly with food (Cherubini 2010; RS 2008). Resources for such 'second generation' biofuels include straw, woody residues from forestry or the waste stream, and purposely grown energy crops. Before these resources can be effectively utilised for biofuels however, significant leaps in technology are required. Whereas bioethanol from plant starch requires conventional brewing technology, lignocellulosic materials require considerably more processing to break down the natural recalcitrance inherent to these materials. It is possible however, that dedicated energy crops could be bred to achieve not only a high yield, but have cell wall characteristics that are easier to process (RS 2008). Although future-'second generation' biofuels are not yet in production in the UK, it is important to ensure that these future fuels are sustainable.

1.2. GHG Reporting Methodologies

The GHG balances and sustainability implications of biofuel supply chains can vary significantly, depending on the biomass feedstock type, the production process, and by how the GHG emission balance is calculated. Maintaining public confidence in biofuels not only requires the Government and the biofuels industry to find effective ways to identify, measure and manage their potential negative impacts (RFA 2010), but for there to be a consistent calculation method. GHG reporting methodologies have been developed, and these appear in the main renewable energy policy developments of the UK and Europe. Other GHG reporting methods have also evolved in order to measure the GHG balance of general products and services.

The reporting methodologies determine how the overall GHG balance of a biofuel should be calculated based on the International Organisation for Standardisation (ISO) Standards on LCA (BSI 2006). They specify which emission sources should be included and how emissions should be split when a process yields two or more products. Allocation, or attributing emissions between a main product and its co-products, is an important issue in LCA, as it can be done different ways, and can greatly affect the results (Gnansounou et al. 2009; Kaufman et al. 2010; Mendoza et al. 2008). The ISO Standards recommend that, if possible, allocation should be avoided by system expansion. This assumes that the co-product can displace another product, which now no longer needs to be produced, and the avoided emissions are credited to the main product. This method of dealing with co-products is data-intensive, and there can be a variety of products to displace. Alternatively, emissions can be allocated between the main product and the co-products according to physical relationships such as mass or energy content, or by alternatively by others, such as price (BSI 2006). A disadvantage of allocation by mass is that GHG emissions may mostly be allocated to the waste from acquiring something of high value (e.g. diamond mining). A disadvantage of allocation by energy content is that not everything has a readily available energy-content (for example, chemicals from a bio-refinery). Though price can be a good representative of what drives business decision-making, it may not necessarily be the main influence of production (Bauen et al. 2008). Out of all the allocation methods, allocation by price may be more widely applicable, though the results may vary over time and location (Singh et al. 2010; Weidema 2003).

2. Background

2.1. GHG Reporting Methodologies and UK Biofuel Producers

There are currently three GHG reporting methodologies adopted in policy and legislation that biofuel producers in the UK can potentially use: The Renewable Transport Fuel Obligation (RTFO), the European Union (EU) Renewable Energy Directive (RED), and the Publicly Available Specification 2008:2050 (PAS2050). These all have differences in their approach to measure GHG emissions. The RED and RTFO have been developed in response to concerns over biofuel sustainability, while the PAS2050 is applicable to any product or service. Each has valid points for GHG measuring and reporting and subsequent policy analysis. Over time we will see some of the methodologies be revised, updated and even merged, and it is possible that eventually one will 'rule them all'.

Probably the main reason why the methodologies have taken different approaches to GHG emission reporting is that the ISO Standards on LCA can be interpreted in different ways. GHG reporting methodologies are relatively new, so should be open to integration of new scientific ideas and only use the most recent and accurate data (BSI 2008b). It is important that methodologies can correctly identify relevant sustainability issues and address indirect effects, for example, of residue removal from arable land, or land use change. The results should be compared with an alternative product or service to prove if GHG emissions are actually saved. The GHG balance of the biofuel or bioenergy supply chain must be analysed from a life-cycle perspective (Bauen et al. 2008; Cherubini 2010) and the method chosen should provide meaningful information to answer a specific question.

2.1.1. Renewable Transport Fuel Obligation (RTFO)

The RTFO is one of the original UK Government's policies for reducing GHG emissions from road transport. It imposes a "legal obligation on fossil fuel producers to produce or supply renewable transport fuel" and defines the basis for biofuel producers to report their GHG emissions (Black et al. 2011; RFA 2010). It also introduces sustainability principles to consider environmental and socio-economic impacts of biofuel production. From April 2008, it was intended to deliver carbon savings of 2.6-3.0 million tonnes by 2010 through encouraging the use of renewable fuels. This saving is based on a biofuel blend of 5% by volume, though the target year has been postponed to 2013/2014 due to concerns with biofuel sustainability. The original methodology for the RTFO was written by E4Tec (Bauen et al. 2008), however this has been highly modified since the publication of the Renewable Energy Directive (RED). Though the RED calculation methodology now mostly replaces that used in the RTFO this study examines the original RTFO methodology as it provides a different view on how the GHG calculations should be performed, with its own valid interpretations of the ISO Standards.

2.1.2. EU Renewable Energy Directive (RED)

The RED (EC 2009) is produced by the European Parliament and the Council of the European Union as part of the Climate Change Package agreed in December 2008 (Black et al. 2011). Produced in April 2009, it promotes energy from renewable resources, and provides targets for participating Member States to commit to. The UK target is to produce 15% of all energy from renewable resources, including a minimum 10% of renewable transport fuels (EC 2009). The Directive provides reporting guidelines with mandatory components which are expected to be implemented by Member States by December 2010. Recently, a draft standard has been released that focuses on calculation methods for biomass to energy applications, but this is not complete (CEN 2010).

The RED includes both ‘first’ and ‘second’ generation biofuels, as well as electric vehicles. It states that biofuel production should be sustainable. The sustainability criteria are not yet fully developed, but they will ensure that biomass is not grown on biodiverse, protected or endangered lands. Carbon released from land conversion must be included in the GHG calculations. The GHG savings from biofuels should be at least 35% before January 2017, 50% after, and 60% after January 2018 for installations that start on or after 1 January 2017. Details are provided to how the GHG emissions and GHG savings from biofuel supply chains should be calculated. The RED requires that Member States should provide a ‘guarantee of origin’ for electricity and heat from biomass. These guarantees are required to prove the energy is renewable, rather than sustainable.

2.1.3. Publicly Available Specification 2050: 2008 (PAS2050)

The PAS2050 methodology (BSI 2008b) is the first attempt to provide an applicable and consistent approach to accounting for the GHG balance from any product or service (Sinden 2009). It was published in 2007 by the British Standards Institution (BSI) at the request of the Carbon Trust and DEFRA (Department of the Environment, Food, and Rural Affairs) in response to a “broad community and industry desire for a consistent method for assessing the life cycle GHG emissions of goods and services”.

The main principle of PAS2050 is that the assessment uses relevant, accurate data, is complete, consistent and transparent so that the calculations are repeatable. It will allow consumers to compare similar products according to their GHG ‘footprints’, and facilitate the development of a ‘business-to-business’ database of ‘foot printed’ products (BSI 2008b). Biofuel producers will not tend to apply the PAS2050 methodology to their supply chain as they are obligated to report to the RTFO, and soon to the RED, whereas PAS2050 accreditation is voluntary. The methodology is not specialised for biofuels. The PAS2050 method, however, is currently being used for food products. Wheat producers will therefore legitimately be able to measure their emissions differently depending on if they send their grain to a biofuel producer, or, say, to a bread manufacturer.

2.2. Objectives

The aim of this study is to compare the three main GHG emission reporting methodologies that could potentially be used by biofuel producers in the UK. The sensitivity of the overall GHG balance to the methodology chosen is tested using a typical example of wheat grain to bioethanol study (AEA Technology & North Energy Associates 2008), and a theoretical study of lignocellulosic-bioethanol from wheat straw (Slade et al. 2009; Slade 2009). It is assumed that the wheat crop is grown in the UK, and no land use change has occurred. The effects of straw removal are explored. Indirect land use change (ILUC) is not included as the methodologies have not yet developed a method for calculating this. The GHG savings are calculated by comparison with conventional petrol. The GHG included are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). From this point onwards 'emissions' will refer to GHG emissions. Other GHG's listed in the IPCC are not included as the aim of the study is to generate results in order to examine the impacts of the methodologies.

3. Methodology

3.1. Life Cycle Assessment

The following subsections describe the LCA's for wheat grain and wheat straw to bioethanol. The functional unit of the LCA study is 1 gigajoule (GJ) of bioethanol at the factory, ready to be blended and distributed to the end user. The final unit of measurement is the CO_2 equivalent (CO_2 eq.) emissions released during production of the biofuel (kg CO_2 eq./GJ). The methodologies adopt different global warming potentials: the PAS2050 methodology uses 1, 25, and 298kg CO_2 eq. and the RED and RTFO use 1, 23, 298kg CO_2 eq. for 1 kg CO_2, CH_4 and N_2O, respectively. A simplified mass balance is provided in Figure 1.

It must be stressed that the results of the lignocellulosic-bioethanol production process in this paper are based on theoretical data (Wooley et al. 1999), and may not be representative of the most advanced lignocellulosic bioethanol plants. The results have been generated primarily for comparative rather than absolute purposes; the aim of the study is to examine the effect of the methodologies on the results.

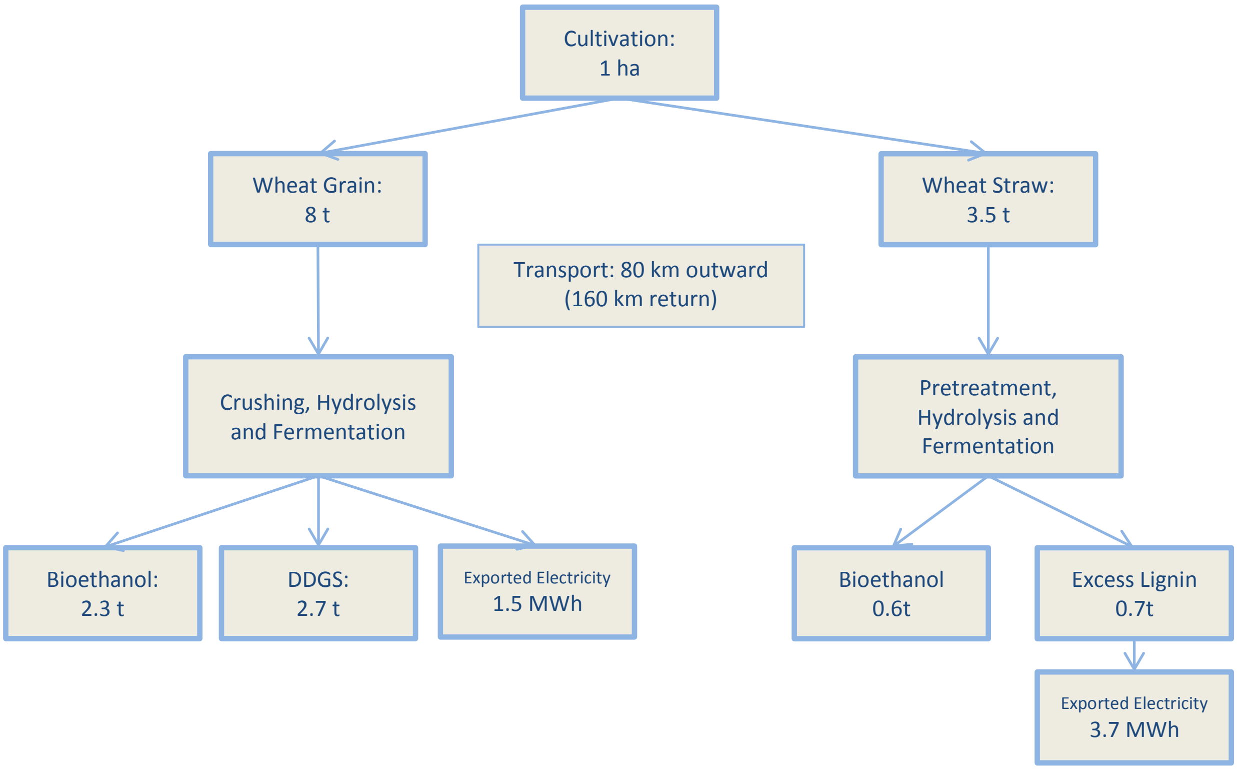

Figure 1 Flow diagram of bioethanol production from wheat grain and wheat straw.

The reporting methodologies were reviewed to identify major differences in their calculations. When bioethanol is produced from wheat straw it is assumed that lignin is combusted for electricity production. The exported electricity is treated differently across methodologies. The emission credits awarded to exported electricity are detailed in Table 1. These figures are not those officially recommended in the reports, as the RED and PAS2050 do not provide a specific emission factor for neither average nor marginal electricity (RFA 2008a). It should be noted that the PAS2050 method that recommends electricity emission factors from the Carbon Trust are used, though these are not in the public domain. The RTFO provides an aggregated figure of 0.472 and 0.382 kg CO_2 eq./kWh of grid and marginal electricity, respectively. Electricity emission factors can also be dependent on the method in which they are calculated and the assumptions made on, for example, the thermal efficiency of natural gas-fired plant; therefore for the purpose of this study, in each methodology we have applied consistent emission factors for average and marginal electricity.

Emissions from biofuel combustion are assumed to be zero in the RED and RTFO methodologies. The PAS2050 method does not state this; therefore here non-CO2 emissions are included, assuming a rate of 0.04kg CH_4 and 0.007kg N_2O/GJ (AEA Technology & North Energy Associates 2008). The same assumptions are made for non-CO_2 emissions from lignin combustion, though it must be noted that it is not clear that these are included or excluded in the RED or RTFO methodologies. These emissions are however, expected to be small.

Table 1 Electricity credits assumed in this study for marginal and grid electricity.

			Emissions		
	Primary Energy	***Carbon Dioxide***	***Methane***	***Nitrous Oxide***	***Total GHG***
Electricity Credit	*MJ/kWh*	*kg CO_2/ kWh*	*kg CH_4/ kWh*	*kg N_2O/ kWh*	*kg CO_2 eq./ kWh*
Gross Grid Credit (a)	11.088	0.541	0.00146	0.000020	0.583
Marginal Electricity Credit (b)	6.962	0.371	0.00044	0.000001	0.383

Notes:

(a) Based on BEAT2

(b) Assume electricity only generation from natural gas, with conversion efficiency of 54.5% (North Energy 2010)

3.1.1. Wheat Grain to Bioethanol

The emissions for UK wheat cultivation were based on the grain-bioethanol assessment performed by the Biomass Environmental Assessment Tool (BEAT) v.2, produced by AEA Technology & North Energy Associates 2008, on behalf of DEFRA and the Environment Agency. Farm machinery manufacture and maintenance is excluded for consistency with all methodologies. One transport stage (from field to factory, assuming an average distance of 80km, or 160km return) is retained. The average yield of wheat grain and straw is 8 and 3.5t/ha, respectively. The energy content is calculated using data from the Phyllis Database (ECN n.d.), based on moisture contents given in BEAT2 (Table 2). The price of wheat grain has been updated according to the most recent Farmers Handbook (average winter wheat £121.33/t, Nix 2011)). The straw should be priced at where it occurs, in this case, during combine harvesting, and straw 'on field' can be priced between £0 and £43/ha. The national average straw price is £8.57/ha, though this is double in the west of the UK, and can triple during a year or poor supply (Nix 2011). The price assumed for this study is £35/t, for straw that is already baled by the farmer. In a similar way, in BEAT2, the price of, already processed and dried, dry distiller's grains and solubles (DDGS) is £80/t. This is an interesting issue of price and allocation however, and should be further explored. It should be noted that the price of straw may increase once lignocellulosic bioethanol plants are established (Kaufman et al. 2010). The energy content of bioethanol and DDGS is 26.8 and 16GJ/t, respectively (Alberichi & Hamelinck 2010). The bioethanol plant in BEAT2 utilises a natural gas-powered CHP boiler to provide heat for the production process. As a result, excess electricity generated by this is exported to the grid. The mass balance and consumption of reactants and primary energy are provided in Table 3.

Table 2 Lower heating value of wheat grain, straw and dry distiller's grains and solubles (DDGS)

	Wheat Grain	*Wheat Straw*	*DDGS*
Gross calorific value measured dry and ash free, HHVdaf (MJ/kg)	19.573	20.998	20.897
Hydrogen fraction, H (% by dry weight)	5.05	6.12	3.38
Moisture content, w (% by weight as received)	20	25	25
Ash fraction, ash (% by weight as received)	7.3	7	39.4
Net calorific value measured as received, LHVar (MJ/kg)	*13.15*	*13.03*	*8.33*

Table 3 Mass balance of inputs and outputs for bioethanol production from wheat grain and wheat straw.

Stage	Units	Input	Output
Wheat Cultivation			
Seeds	kg/ha	175	
Farm yard manure/slurry	kg/ha	3375	
N Fertilizer	kg N/ha	197	
P Fertilizer	kg P_2O_5/ha	39	
K Fertilizer	kg K_2O/ha	48	
Pesticides	kg/ha	1.03	
Wheat Grain	t/ha		8.00
	odt/ha		*6.4*
Wheat Straw	t/ha		3.50
	odt/ha		*2.2*
Processing from Wheat to Bioethanol			
Heat Input	MJ/t wheat input	1625.79	
Electricity Input	kWh/t wheat input	46.63	
Chemicals			
NaOH (49%)	kg/t wheat input	12.91	
$(NH_4)2HPO_4$ (21%)	kg/t wheat input	8.53	
H_2SO_4 (93%)	kg/t wheat input	8.50	
Enzyme AMG	kg/t wheat input	0.71	
Enzyme Alpha Amylase	kg/t wheat input	0.40	
$CaCl_2$	kg/t wheat input	0.28	
Bioethanol	kg/t wheat input		291.92
Dry distillers grains and solubles	kg/t wheat input		330.08
Exported Electricity- from fossil fuel CHP boiler	kWh/t wheat input		187.37
Processing from Wheat Straw to Bioethanol			
Cellulase	FPU/t straw input	4608000	
Electricity	kWh/t straw input	144.00	
Water	m^3/t straw input	60.67	
Chemicals			
SO_2	kg/t straw input	12.38	
NaOH (50%)	kg/t straw input	23.17	
NH_3 (25%)	kg/t straw input	1.89	
H_3PO_4 (50%)	kg/t straw input	0.42	
Defoamer	kg/t straw input	0.45	

$(NH_4)2PO_4$	kg/t straw input	2.21	
$MgSO_4.7H_2O$	kg/t straw input	0.10	
Bioethanol	kg/t straw input		175.20
Excess Solid Fuel	kg/t straw input		201.60
(Electricity generated from excess solid fuel)	kWh/t straw input		1062.43

3.1.2. Wheat Straw to Bioethanol

Where applicable, the emissions from wheat cultivation that are attributed to wheat straw are based on BEAT2. Again, farm machinery manufacture and maintenance are excluded and one transport stage is retained, adjusting the emissions from transport according to Whittaker et al. 2009 to take into account the low bulk density of straw (150kg/m^3).

Emissions from the enzymatic conversion process from lignocellulosic-bioethanol are calculated using Slade, (2009). The study has been modified to represent a solid input stream of wheat straw, instead of a wheat straw and forest residue mixture. The cellulase requirement is adjusted to 5.8x10^6 filter paper units (FPU) per oven dry tonne (ODT) straw, assuming a cellulase requirement of 15FPU per gram of cellulose (Wooley et al. 1999), and a cellulose content of 362-406g/kg dry matter, or about 38.4% (Akin 2007). It is assumed that excess solid lignin fuel is used to generate electricity which is exported to the grid. No details are provided in Slade, 2009, for the total amount of lignin generated, therefore CH_4 and N_2O emissions from lignin combustion cannot be included. These are, however, expected to be small. For excess solid fuel, a higher heating value of 22.3GJ/ODT was provided from Slade, 2009, though conventionally a lower heating value (LHV) should be used. The moisture content is not stated in Slade, 2009, therefore this number must be used as an estimate for the LHV. The conversion efficiency of the boiler combusting lignin is 85% (Wooley et al. 1999). The mass balance and consumption of reactants and primary energy are provided in Table 3.

4. Results and Discussion

4.1. Review of GHG Reporting Methodologies

Defining the GHG reporting methodologies is difficult as some aspects are vague and open to interpretation. The methodologies lack both definitions and demonstrations to how different products should be regarded in calculations. Different interpretations, and different assumptions of where products should be priced, or which credits to award, will dramatically affect the calculation methods and subsequently, the results. The interpretations made in this study are summarised in Table 4 and discussed in the following section.

The PAS2050 methodology could be considered to be the simplest method: requiring that during the production, use and disposal of a product or service, all sources of emissions that make a 'material contribution' should be accounted for. This may require more guidance however, for reporting specifically on biofuels. The equation provided in Annex V Section C of the RED was specifically written for assessing emissions from biofuels. It does not, however, provide enough details for the reporting calculations to avoid differences in interpretation, and hence is not practical for use in regulation. The default figures provided by both the RED and RTFO are neither detailed nor referenced, and are therefore not transparent. It should be noted, however, that transparency is beginning to emerge with the development of the BIOGRACE website (www.biograce.net) which provides more detailed information on emission factors that will be used to support RED calculations.

The differences in the calculations are a consequence of the differences in approaches each reporting methodology takes to LCA, mainly due to the allocation of co-products. This will depend on whether the method tends toward attributional or consequential LCA (Brander, Tipper, et al. 2009). Attributional LCA (ALCA) examines the emissions that arise from the life cycle of a product, but not the broader indirect effects that arise due to changes in the output of that product and its co-products, as in consequential LCA (CLCA, Brander, Tipper, et al. 2009, Kaufman et al. 2010). These two approaches therefore will have a different scope, and it is natural that they will yield different results.

LCA's tend to map or account for the emissions that a product or service is accountable for (Sandén & Karlström 2007), and the results are not usually compared with alternative product systems (Weidema 2003). In ALCA co-products are allocated emissions rather than credited via system expansion. CLCA follows the principle described in the original RTFO methodology that substitution credits should be applied to account for "any consequences of a marginal increase in demand' due to biofuel production (Bauen et al. 2008). The RED has the view that to account for co-products via co-product substitution credits, as in CLCA, is a method best suitable for policy analysis but maybe not for 'regulation of individual economic operators and individual consignments of transport fuels' (EC 2009). The recent report "Biofuels: ethical issues" (Nuffield Council on Bioethics 2011), recommends that biofuel regulation and reporting should consider who is directly responsible for a net change in emissions due to biofuel production. In this case ALCA is the recommended approach as producers have immediate control over any direct emissions they cause during production. CLCA, on the other hand, is better suited for policy analysis, where the overall impact of implanting the biofuel targets is considered in a wider, even global context of producers and consumers (Nuffield Council on Bioethics 2011).

The RTFO methodology was originally described as a 'partially consequential' methodology (Brander, Tipper, et al. 2009); however it is being adapted to follow the RED's, and likewise PAS2050's more ALCA approach. Neither the PAS2050 nor RED can be described as being

100% ALCA, mainly due to how exported electricity is credited, and the PAS2050 recommends that substitution credits are used where 'practicable' (BSI 2008b).

4.2. LCA of Bioethanol Production

The different LCA methodologies give different results for bioethanol from both wheat grain and wheat straw despite being based on the same production pathways. This is due to assumptions and interpretations to how the calculations are carried out. Across the methodologies total emission savings for wheat grain ethanol (compared to conventional petrol) range from 24% to 57%, and for lignocellulosic-bioethanol the range is greater: from 47% to 129%. The emission savings estimated by this study do not match the default figures provided in the RED and RTFO (Table 5). It is difficult to identify the reason for this as neither the RTFO nor RED provide references for how the default figures were calculated. Differences may be due to interpretations of the calculation methods, or different assumptions in the production process, such as the yield, inputs or conversion process details. The RED default number for bioethanol from wheat grain does not satisfy the 35% emission saving target.

It is important to note that the results from bioethanol production from wheat grain and straw are not strictly comparable, as they are being produced at different scales and the lignocellulosic-bioethanol production chain is theoretical. The main aim of the study is compare effect of GHG reporting methodology to the results. It should be noted that these results are dependent on the price of straw assumed, and the more expensive straw becomes, the greater the differences will become.

Table 4 Summary on how emissions are allocated between co-products of bioethanol production from wheat grain and wheat straw.

						Processing		
	Description			Cultivation		Wheat To Bioethanol		
Methodology	Cultivation Step	Processing Steps	Exported Electricity	Wheat	Straw	Bioethanol	DDGS	Electricity
RED (DDGS no allocation)	Everything is allocated to wheat	Everything is allocated to Bioethanol	Credited with emissions from electricity generated from natural gas	**100%**	**0%**	**100%**	**0%**	Credit: 0.383 kg CO_2 eq./kWh
RED (DDGS allocated)	Everything is allocated to wheat	Emissions allocated between Bioethanol and DDGS by energy content	Credited with emissions from electricity generated from natural gas	**(59%)(a)**	**0%**	**59%**	**41%**	Credit: 0.383 kg CO_2 eq./kWh
PAS2050	Straw is allocated by price.	DDGS is allocated by price.	Credited with emissions for average grid electricity	**75% (b)**	**25% (b)**	**84%**	**16%**	Credit: 0.583 kg CO_2 eq./kWh
Original RTFO	Straw is allocated by price	DDGS is awarded substitution credits for animal feed.	Credited with emissions from marginal electricity generation	**89% (c)**	**11%(c)**	**100%**	Credit: 491 kg CO2 eq./t animal feed	Credit: 0.383 kg CO_2 eq./kWh
				Straw to Ethanol				
RED	Everything is allocated to wheat	As lignin is used to generate electricity it is allocated by energy content according to energy content of lignin.		**100%**	**0%**	**55%**	**n/a**	**(lignin) 45%**
PAS2050	Straw is allocated by price.	Everything is allocated to Bioethanol	Credited with emissions for average grid electricity	**89%**	**11%**	**100%**	**n/a**	Credit: 0.583 kg CO_2 eq./kWh
Original RTFO	Straw is allocated by price	Everything is allocated to Bioethanol	Credited with emissions from marginal electricity generation	**89%**	**11%**	**100%**	**n/a**	Credit: 0.383 kg CO_2 eq./kWh

(a) Cultivation is split 59% and 41% between wheat grain and DDGS.
(b) This is the accumulative allocation between bioethanol and straw, considering that emissions from cultivation are split between bioethanol, DDGS and straw by price.
(c) This is allocation by price between wheat grain and wheat straw, but not DDGS. DDGS is awarded substitution credits.

Table 5 Total GHG emissions for bioethanol production from wheat grain and wheat straw, with % savings compared to conventional gasoline.

	Total Fuel Chain Emissions		Default Figure	
Wheat Grain to Bioethanol	(kg CO_2 eq./GJ)	% net Savings	(kg CO_2 eq./GJ)	% net Savings
RED (DDGS = residue)	63.3	24	57	32
RED (DDGS = co-product)	37.6	55	57	32
PAS2050	45.2	46	-	-
Original RTFO	36.0	57	70	16
Wheat Straw to Bioethanol				
RED	44.8	47	11	87

PAS2050	24.5	129	-	-
Original RTFO	19.9	76	13	84
Gasoline	**83.8***			

*** Figure provided by the RED –it is important to note thate the % savings will depend on emission factor assumed for gasoline.**

4.2.1. Exported Electricity

The most important difference in the methodologies is how exported electricity is treated in the calculations. In all cases the same product is produced: electricity, though the calculations, and hence, the calculated results are different (Figure 2, Figure 3). Exported electricity has a major effect in the straw-bioethanol study, where it is produced in large quantities. This is however, based on limited data provided for the calorific value of lignin (Slade 2009).

In the RED, if the lignin is not used for electricity it is regarded as a "residue from processing" and attributed no emissions. If it used to produce electricity it is considered to be a co-product and is allocated by energy content according to the energy content of the lignin, not the electricity. In contrast, the PAS2050 and RTFO do not allocate emissions to lignin, but award credits to the generated electricity. PAS2050's credits are based on average electricity production, which provide a greater credit than the marginal emissions from electricity generated from natural gas in the RTFO (Figure 3). In the RED, when DDGS is treated as a co-product the electricity credits are lower as they are shared 59% and 41% between bioethanol and DDGS.

In all three methodologies, exported electricity produced from fossil fuels (in the CHP plant) is always awarded with avoided electricity credits. Details are not clear as to how the methods award credits, however the following assumptions are made: the RED explains that "the greenhouse gas emission saving associated with excess electricity shall be taken to be equal to the amount of greenhouse gas that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit" (EC 2009). Therefore, this is assumed to correspond to marginal emissions. The RTFO also awards marginal credits (Brander, Tipper, et al. 2009). The PAS2050 method states that: "the avoided GHG missions associated with the displaced product represent the average emissions arising from the provision of the avoided product" (BSI 2008b).

4.2.2. Co-product Allocation

In the RED, determining whether a material is a co-product or a residue is a serious issue, yet there is a lack of definitions of either. It allocates zero emissions to "agricultural residues" and "residues from processing" but allocates co-products by energy content. The original RTFO and PAS2050 methods recommend that co-product allocation should be avoided by applying system expansion, but if this is not practicable, allocation should be done by market value.

4.2.2.1. Straw

Co-product allocation calculations with straw are applicable to both the wheat and straw-bioethanol pathways. Straw is, no doubt, an agricultural residue and is hence not attributed any emissions from wheat cultivation in the RED. A significant problem with attributing no emissions to "residues" and "residues from processing" is that it implies they are a waste. Straw-bioethanol producers will therefore not have to account for the sustainability of their straw source, which is interesting.

In the updated, 'RED-ready' RTFO, by-products and co-products are more carefully defined, more so, than in the RED. A product is a by-product if it represents less than 10% of the farm or factory gate value, and a co-product if more (RFA 2010). Consumers of 'by-products' have "little influence on the sustainability of the production processes for the original product" and do not need to report on the sustainability of their origin (RFA 2010). Based on the prices used in this assessment, straw represents 10-13% of the total factory gate value, therefore is bordering on what should be considered a co-product. In the directory of by-products in Annex B of the 'RED-ready' RTFO Guidance, straw is not listed among the by-products (RFA 2010), yet it seems to be treated as so in the rest of the methodology. It is too vague, however, to be said to be inconsistent. In this study, straw is assumed to be a co-product. As no substitution credits are provided by the RTFO, straw is allocated by price. When the RTFO is fully implemented into the RED, however, straw may be referred to a "residue".

The PAS2050 methodology does not prescribe specific circumstances; therefore straw is regarded as a co-product. However, in the only relevant example given in the PAS2050 Guidelines (for croissant production), this is not demonstrated (BSI 2008a). As substitution credits are not provided by the PAS2050, emissions will be allocated to straw and DDGS according to price.

If straw is included in the total emission, or allocated by price, it makes a difference of 398kg CO_2 eq./ha, or 6.4kg CO_2 eq./GJ to grain-bioethanol, and 24.2kg CO_2 eq./GJ to straw-bioethanol. The greater impact to straw-bioethanol is due to the lower yield of bioethanol from straw per hectare. Allocating emissions to straw decreases the emissions for wheat-bioethanol but increases them for straw-bioethanol.

4.2.2.2. Dry Distillers Grains and Solubles

In the grain-bioethanol study, the treatment of DDGS in the calculation methodology affects the results. Using the descriptions provided in the RED, DDGS is a "residue from processing", however most practitioners will sell DDGS for animal feed, and would regard this as a co-product. The effect of this was tested in the results (Figure 2). When DDGS is a co-product, emissions from cultivation, transporting and conversion are shared 59% and 41% between bioethanol and DDGS, respectively, based on their energy content. Otherwise the emissions are 100% allocated to bioethanol. When DDGS is treated as a co-product, therefore, the overall emissions are lower (37.6kg CO_2 eq./GJ), compared to when not (67.3 kg CO_2 eq./GJ), a difference of 25.6 kg CO_2 eq./GJ. The substitution credits, awarded in the RTFO reduce overall emissions by 20.90kg CO_2 eq./GJ. These credits are based on displacing soy meal imported from North America. The RED recommends allocation by energy content, as this method is "easy to apply, is predictable over time, minimises counter-productive incentives and produces results that are generally comparable with those produced by the substitution method". From the results, this statement appears to be true; however it may simply be a co-incidence and the same may not be seen in other studies.

The PAS2050 method allocates DDGS by price. The conversion and transport stages are shared 84% and 16% between bioethanol and DDGS, respectively, and the cultivation phase is shared 75% and 25% between wheat (and DDGS) and straw, respectively.

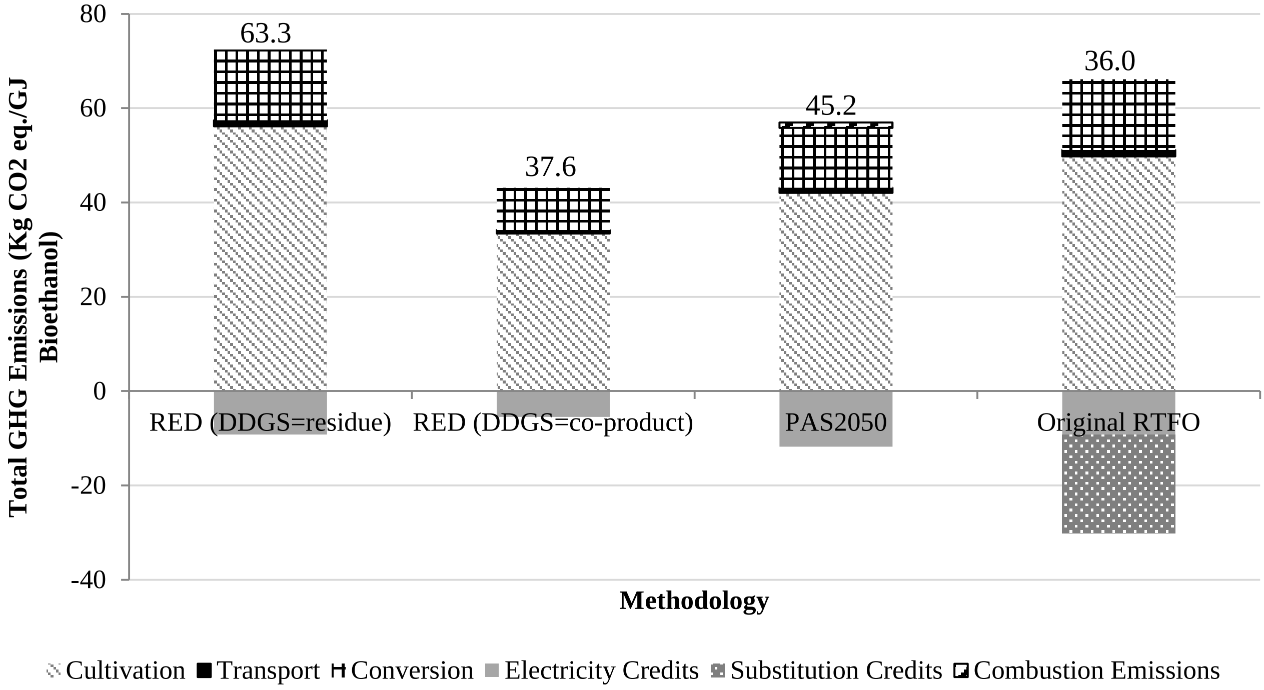

Figure 2 Breakdown of sources of emissions from bioethanol production from wheat grain calculated according to different GHG reporting methodologies.

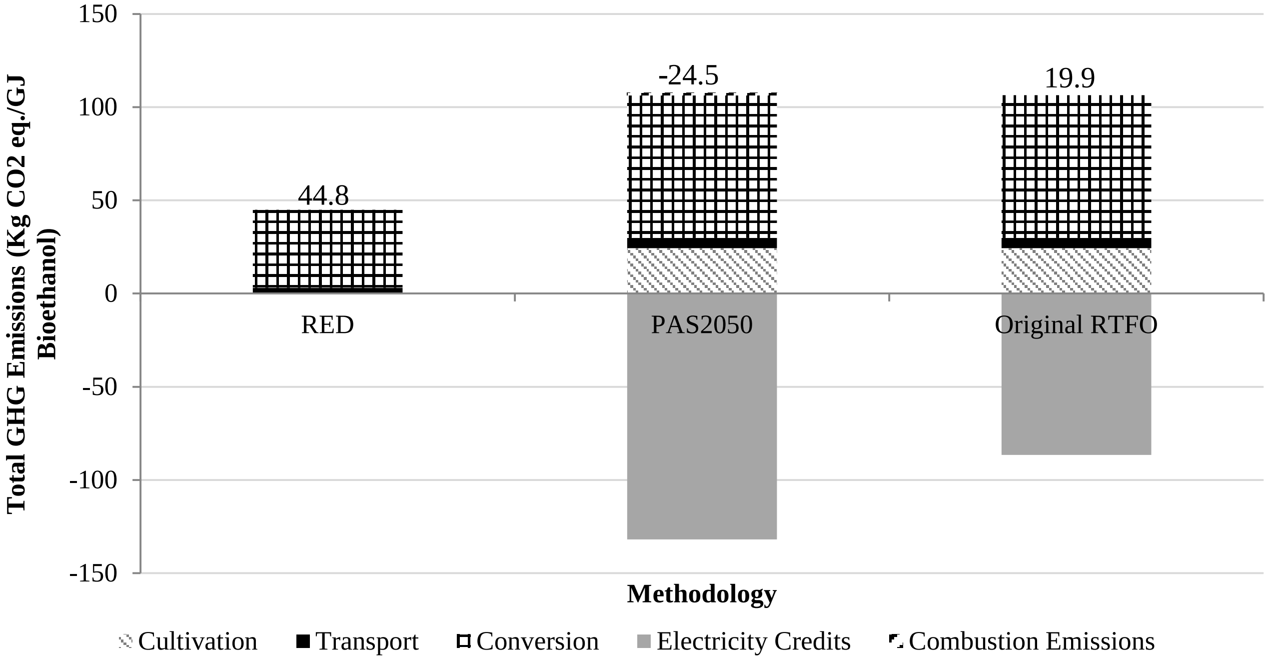

Figure 3 Breakdown of sources of emissions of bioethanol production from wheat straw calculated according to different GHG reporting methodologies.

4.2.3. Overall Emissions

Overall, for grain-bioethanol production the RED methodology gives the highest fuel chain net GHG emissions when no co-products are included. The RTFO methodology gives the lowest mainly due to the substitution credits awarded to DDGS (Figure 2).Without this credit, the RED will give the lowest result, but only when DDGS is allocated by energy content, otherwise the PAS2050 will give the lowest result.

For straw-bioethanol, the PAS2050 methodology has the lowest net emissions per GJ bioethanol, mainly due to emission credits awarded for exported electricity generated from lignin. Different assumptions on how exported electricity is treated in the calculations explain why the range of emission savings is so great for straw-bioethanol. The highest result is calculated using the RED methodology, due to the lack of these credits. This is true even despite the PAS2050 and RTFO methodologies incurring emissions from cultivation by sharing these between wheat and straw.

Negligible differences in transport emissions are seen between methodologies, as this only contributes about 2% of the total supply chain. In the PAS2050 method, emissions from biofuel combustion represent 2% of the total emissions. Emissions from combustion are assumed to be 0 kg CO_2 eq. in the other methodologies. Differences due to different GWP assumptions are also negligible.

4.3. Direct Effects of Straw Removal

As previously mentioned, in the RED straw is not attributed any upstream emissions from cultivation, and in doing so technically defines straw as a waste or by-product. This assumes that in the absence of the bioenergy system, it would not have been used for anything else and would have been left on the soil to decompose (RFA 2010).There are no suggestions on how to account for any direct effects of removing straw from land. There may also be indirect effects of diverting straw from its existing markets, this being relevant to CLCA, which is better suited for policy analysis than biofuel reporting and regulation (Nuffield Council on Bioethics 2011).

The methodologies do not prescribe any particular calculation methodology for straw removal or incorporation. The exception to this is the RTFO, which assumes that the alternative fate of crop residues is that they are left on the ground to rot, only releasing biogenic CO_2 in the process, which is regarded as carbon-neutral (Bauen et al. 2008). This is interesting as the IPCC calculations include N_2O emissions from crop residues (De Klein et al. 2006); suggesting the RTFO methodology does not accurately account for these emissions. The RED also does not mention this particular source of emissions, though it may be implicitly included in the "emissions from cultivation" stage (RED, Annex V, Section C).

Straw removal may cause changes in soil carbon content, which producers are required to report in RED and PAS2050 calculations. Straw incorporation increases soil carbon stocks at a rate of 1.69 t CO_2/ha/year in the first 20 years, until an equilibrium carbon-content is reached. Straw removal can however, reverse this effect (Powlson et al. 2008). When straw is used to displace natural gas, carbon savings of up to 21.27 t CO_2 eq./ha/yr can be achieved; a much greater amount than the carbon sequestered in the soil, particularly when this can continue for years. The maximum savings of straw-bioethanol were estimated at 133%, saving 1.63 t CO_2 eq./ha/yr.

Straw removal may also cause nutrient loss in the soil, which must be replaced with artificial fertilizers to avoid a drop in subsequent yields (Cherubini 2010; Punter et al. 2004). Residue incorporation is necessary for the recycling of nutrients, especially K, P and S, but less so for

N, which is typically removed in the grain component (Whitbread et al. 2003). Brander, and Hutchison et al., 2009, estimates this penalty at 0.038 and 0.0043 t CO_2 eq./t wheat straw including and excluding nitrogen-based fertilizer displacement, respectively. There are, however, various estimates for the value of the fertilizer penalty in literature (Table 6), and they reduce the total emission savings by 1 to 44% (Figure 4). Therefore, the indirect emissions from the fertilizer penalty could potentially have a large impact on the results.

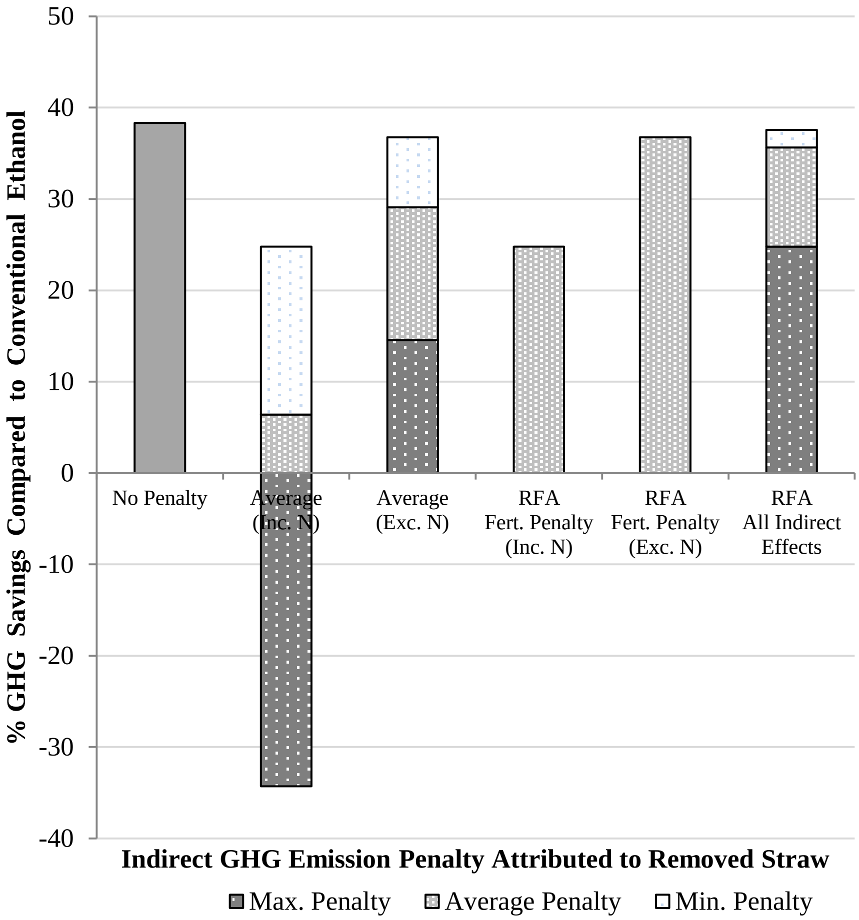

Figure 4 GHG emission savings for wheat-straw based bioethanol (PAS2050) including a fertilizer penalty from straw removal. Average fertilizer penalties (including and excluding N) are shown, alongside estimates from the RFA (Brander, Hutchison, et al. 2009).

The fertilizer penalty is, however, difficult to measure in practice, with variations in the results mainly being attributed to environmental conditions (Gabrielle & Gagnaire 2008). It is usually estimated from trials on the effect of yield when straw is either removed or incorporated into the soil. Though modelling may show that that straw incorporation increases yield due to nutrient recycling (Gabrielle & Gagnaire 2008), there is evidence that it in fact decreases yield due to N immobilisation (Limon-Ortega et al. 2008; Liu et al. 2011), poor seed to soil contact, poor seedling emergence and phytotoxin production from straw decomposition (Morris et al. 2009). In these cases the 'fertilizer penalty' does not reflect commercial practice, where typically fertilizer applications are made independent of straw removal (RS 2008; Whittaker et al. 2009). Therefore, greater agronomic knowledge of any potential indirect effects of straw removal is required, which is also highlighted by the RED.

Straw also has additional values to soil other than potential nutrient recycling, and it is difficult to measure, and even to quantify the direct effects from straw removal. There is evidence that soil organic carbon (SOC) increases more rapidly when straw is incorporated, being important for general soil health, including soil fertility, structure, microbial activity, water retention and bulk density (Tarkalson et al. 2009). The indirect impacts of affecting these properties are difficult to assess.

Table 6 Summary of fertilizer penalties attributed to straw removal

	Nutrient Content (kg nutrient/t straw)			**Fertilizer Penalty (t CO_2eq./t straw removed)**		
Resource	**N**	**P_2O_5**	**K_2O**	**Including N**	**Excluding N**	**No Details**
Punter et al., 2004	19	3	34	0.20	0.07	
Potash Development Association (a)	-	1.2	9.5		0.02	
Plant Nutrient Content Database (b)	7.6	0.8	14.7	0.08	0.03	
Crop Observation and Recommendation Network (c)	5.0	1.4	9.1	0.05	0.02	
Tarkalson et al., 2009	7.4	1.1	9.4	0.07	0.02	
(Brander, Hutchison, et al. 2009) (d)	-	-	-	0.04	0.004	
Gabrielle & Gagnaire, 2008	-	-	-			0.02
Slade et al., 2009 (d)	-	-	-			0.13

Notes:

(a) (PDA n.d.)

(b) (NRCS n.d.)

(c) (CORN n.d.)

(d) Results are not provided in kg nutrient format.

4.4. Indirect Land Use Change and Lignocellulosic Biofuels

The RED also identifies the need to closely examine potential ILUC impacts of biofuels produced from lignocellulosic material. ILUC is not included in any of the reporting methodologies at present however, as it is difficult to calculate, predict and validate (EC 2010). There are various models and reports on predicting emission from ILUC, though the focus is on '1st generation' biofuels (Bauen et al. 2010; Dehue et al. 2009; EC 2010). It is highly possible that different methodologies will also develop their own ways to calculate emissions from ILUC.

In the original RTFO, substitution credits are awarded to account for the indirect effects of an increased production of co-products. Substitution credits provide a mechanism for quantifying indirect effects. DDGS, for example, is said to reduce the ILUC impacts from bioethanol production by displacing land required to grow animal feed (Bauen et al. 2010). This offsetting is not seen in other lignocellulosic crops, such as miscanthus and SRC, as these crops do not have the benefit of being co-produced with a valuable commodity, such as wheat (RFA 2008b). These crops could however be grown on lower grade marginal land, which may reduce pressure on demand for agricultural land. Lignocellulosic crops are not immune to issues of ILUC however; as they may create economic incentives for land use change (Cherubini 2010).

Recently, it has been recommended that accounting for ILUC should not be exclusive to GHG reporting for biofuels, but be part of a wider, global framework that protects carbon rich and biodiverse lands from destruction (Nuffield Council on Bioethics 2011). Currently, ILUC is not included in the methodologies as there are no agreed means to calculate it.

Considering that ILUC is more suited to CLCA, whereas ALCA is more appropriate for GHG reporting, impacts of ILUC may need to be accounted for through some other mechanism.

5. Conclusions

The RED and RTFO were both developed directly for assessing the sustainability and GHG balances of biofuel production, whereas the PAS2050 is the first methodology to provide an applicable and consistent approach to accounting for the GHG balance from any product and service. All three can be applied to bioethanol production from wheat grain and wheat straw, though using the same input data, each methodology provides a different result.

The different results are a consequence of differences in the calculation methodologies, due to the approach the methodology takes to LCA; whether the method tends toward attributional or consequential LCA (Brander, Tipper, et al. 2009). For reporting purposes, the RED states that ALCA is best as it provides a snapshot of emissions that are released, and attributable to the production and use of the product or service. CLCA, on the other hand is better suited for policy analysis as the potential impacts are applicable to a wider, even global scope. Neither of the methodologies completely adheres to ACLA nor CLCA.

If interpreted literally, the PAS2050 method is the less convoluted method, as it does not provide specific circumstances for calculating emissions from biofuels. The original RTFO provides the most careful definitions of co-products, by-products and wastes; however they are not consistent in the calculations demonstrated, nor are the default figures transparent. The RTFO will soon be completely integrated into the RED, and if this is integrated into UK law then biofuel producers will be obliged to apply it to calculate their emissions. Currently, however, the RED is too vague to be practical for GHG reporting. Key improvements and justifications of methodological decisions are needed, along with precise definitions of co-products, by-products and wastes as different interpretations of these will affect the results. Also, transparent default figures should be provided, which are referenced from published work. Development of sustainability criteria is also required, but this should be linked to wider, global policies for protecting high carbon or biodiverse lands.

Calculations involving exported electricity were the cause of most of the variation in the results between methods. It is treated differently depending on what it is produced from, despite the fact that it is the same product and always displaces the same product: grid electricity. In each of the methodologies, two methods of treating co-products are recommended (system expansion and allocation); therefore there is always scope for differences in interpretation. Allocation methods between co-products could become more important in future bio-refineries where a range of products are produced.

The methods focus on biofuels produced from food crops such as wheat and oilseed rape, with few references to biofuels produced from lignocellulosic biomass, which generated the greatest range of results. This will become more important in the future with the anticipated increase in production of bioethanol from lignocellulosic resources. The treatment of straw, in particularly the RED calculations, needs to be addressed: it is treated as a benign product, when really straw has a multitude of roles both in the soil and as a product. In this study, it is assumed the RTFO and PAS2050 allocate emissions between wheat grain and straw by price, though it could be interpreted as otherwise due to lack of clarity or demonstration. Understanding the effects of utilising residues from crops is important, as there is evidence it affects the overall GHG savings by 1 to 44%, though this may rely on acquiring new and maybe even site-specific agronomic data.

It is not possible to say which of the available methodologies is currently best suited for biofuels, as they all require either clarification or adaptation for biofuel GHG reporting. The most recent and accurate data should be used to correctly assess the impacts of the product or service. There are limited ways that the methodologies can ensure this is done. The methodologies should be careful not to combine ALCA and CLCA approaches so that the allocation methods and calculations provide meaningful information.

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7. References

AEA Technology & North Energy Associates, 2008. *Biomass Environmental Assessment Tool (BEAT2)*, UK: AEA Technology and North Energy Associates. Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=74,153193&_dad=portal&_schema=PORTAL.

Akin, D., 2007. Grass Lignocellulose: Strategies to Overcome Recalcitrance. *Applied Biochemistry and Biotechnology*, 136-140, pp.3-14.

Alberichi, S. & Hamelinck, C., 2010. *Annotated example of a GHG calculation using the EU Renewable Energy Directive methodology*, Ecofys.

Bauen, A. et al., 2010. *A causal descriptive approach to modelling the GHG emissions associated with the indirect land use impacts of biofuels. Final report. A study for the UK Department for Transport*, UK: E4Tec.

Bauen, A., Watson, P. & Howes, J., 2008. *Carbon Reporting within the Renewable Transport Fuel Obligation – Methodology*, UK: E4Tec.

BERR, 2006. *UK Energy and CO2 Emission Projections: Updated Projections to 2020.*, BERR.

Black, M. et al., 2011. Life Cycle Assessment and sustainability methodologies for assessing industrial crops, processes and end products. *Industrial Crops and Products*, In Press, Corrected Proof. Available at: http://www.sciencedirect.com/science/article/B6T77-51XNX70-1/2/bb96c069dae3d5ee5d58b7705a9b9d19 [Accessed February 4, 2011].

Brander, M., Hutchison, C., et al., 2009. *Methodology and Evidence Base on the Indirect Greenhouse Gas Effects of Using Wastes, Residues, and By-products for Biofuels and Bioenergy*, UK: Ecometrica, Eunomia, Imperial College London for the Renewable Fuels Agency and the Department of Energy and Climate Change. Available at: http://www.renewablefuelsagency.gov.uk/sites/renewablefuelsagency.gov.uk/files/_documents/RFA-DECC_Indirect_Effects_of_Wastes_Report.pdf.

Brander, M., Tipper, R., et al., 2009. *Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels*, UK: Ecometrica.

BSI, 2006. *Environmental management — Life cycle assessment — Requirements and guidelines*, UK: British Standards Institute.

BSI, 2008a. *Guide to PAS 2050: How to assess the carbon footprint of goods and services*, UK: British Standards Institute.

BSI, 2008b. *Publicly Available Specification: PAS2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*, UK: British Standards Institute.

CEN, 2010. *Sustainably produced biomass for energy application. Calculation methods for GHG emissions.*, CEN.

Cherubini, F., 2010. GHG balances of bioenergy systems - Overview of key steps in the production chain and methodological concerns. *Renewable Energy*, 35(7), pp.1565-1573.

CORN, Nutrient Removal of Wheat Straw by Baling — Agronomic Crops Network. Available at: http://corn.osu.edu/newsletters/2010/2010-19/nutrient-removal-of-wheat-straw-by-baling [Accessed March 4, 2011].

De Klein, C. et al., 2006. Chapter 11: N2O Emissions from Managed Soils, and CO2 Emissins from Lime and Urea Application. In *IPCC Guidelines for National Greenhouse Gas Inventories*.

DECC, 2010. *UK CLIMATE CHANGE SUSTAINABLE DEVELOPMENT INDICATOR: 2009 GREENHOUSE GAS EMISSIONS, PROVISIONAL FIGURES AND 2008 GREENHOUSE GAS EMISSIONS, FINAL FIGURES BY FUEL TYPE AND END-USER*, UK: Department of Energy and Climate Change.

Dehue, B., van de Staaij, J. & Chalmers, J., 2009. *Mitigating indirect impacts of biofuel production: Case studies and Methodology*, Netherlands: Ecofys.

EC, 2009. *DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*, Belgium: European Commission.

EC, 2010. *REPORT FROM THE COMMISSIONon indirect land-use change related to biofuels and bioliquids*, Belgium: European Commission.

ECN, Phyllis, database for biomass and waste. Available at: http://www.ecn.nl/phyllis/ [Accessed February 4, 2011].

Gabrielle, B. & Gagnaire, N., 2008. Life-cycle assessment of straw use in bio-ethanol production: A case study based on biophysical modelling. *Biomass and Bioenergy*, 32(5), pp.431-441.

Gnansounou, E. et al., 2009. Life cycle assessment of biofuels: Energy and greenhouse gas balances. *Bioresource Technology*, 100(21), pp.4919-4930.

Kaufman, A.S. et al., 2010. Applying life-cycle assessment to low carbon fuel standards--How allocation choices influence carbon intensity for renewable transportation fuels. *Energy Policy*, 38(9), pp.5229-5241.

Limon-Ortega, A., Govaerts, B. & Sayre, K.D., 2008. Straw management, crop rotation, and nitrogen source effect on wheat grain yield and nitrogen use efficiency. *European Journal of Agronomy*, 29(1), pp.21-28.

Liu, C. et al., 2011. Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat-maize rotation field in northern China. *Agriculture, Ecosystems & Environment*, 140(1-2), pp.226-233.

Mendoza, A. et al., 2008. *The Allocation Problem in Bio-Electricity Chains*. Msc. Thesis. Industrial Ecology. Leiden, The Netherlands.

Morris, N.L. et al., 2009. The effect of wheat straw residue on the emergence and early growth of sugar beet (Beta vulgaris) and oilseed rape (Brassica napus). *European Journal of Agronomy*, 30(3), pp.151-162.

Nix, J., 2011. *The John Nix Farm Management Pocketbook* 41st ed., UK: The Anderson Centre.

North Energy, 2010. *Oilseed rape workbook*, Available at: http://www.nnfcc.co.uk/tools/oilseed-rape-workbook?sectorKey=crops-wood-waste&typeKey=technical-reports-tools.

NRCS, Plant Nutrient Content Database | NRCS. Available at: http://www.nrcs.usda.gov/technical/ecs/nutrient/tbb1.html [Accessed March 4, 2011].

Nuffield Council on Bioethics, 2011. *Biofuels: Ethical Issues*, London, UK.

PDA, Nutrients in crop material - Phosphate and Potash Removal by Crops. Available at: http://www.pda.org.uk/others/pandprbyc.html [Accessed March 4, 2011].

Powlson, D.S. et al., 2008. Carbon sequestration in European soils through straw incorporation: Limitations and alternatives. *Waste Management*, 28(4), pp.741-746.

Punter, G. et al., 2004. *Well-to-wheel evaluation for production of ethanol from wheat. A report by the LowCVP fuels working group, WTW sub-group*,

RFA, 2010. *Carbon and Sustainability reporting within the Renewable Transport Fuel Obligation: Technical Guidance Part One*, UK: Renewable Fuels Agency.

RFA, 2008a. *Carbon and Sustainability Reporting Within the Renewable TransportFuel Obligation Technical Guidance Part Two Carbon Reporting – DefaultValues and Fuel Chains*, UK: Renewable Fuels Agency.

RFA, 2008b. *The Gallagher Review of the indirect effects of biofuels production*, UK: Renewable Fuels Agency.

RS, 2008. *Sustainable biofuels: prospects and challenges*, UK: The Royal Society.

Sandén, B.A. & Karlström, M., 2007. Positive and negative feedback in consequential life-cycle assessment. *Journal of Cleaner Production*, 15(15), pp.1469-1481.

Searchinger, T. et al., 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, 319(5867), pp.1238 -1240.

Sinden, G., 2009. The contribution of PAS 2050 to the evolution of international greenhouse gas emission standards. *The International Journal of Life Cycle Assessment*, 14(3), pp.195-203.

Singh, A. et al., 2010. Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: Challenges and perspectives. *Bioresource Technology*, 101(13), pp.5003-5012.

Slade, R., 2009. *Prospects for cellulosic ethanol supply-chains in Europe: a techno-economic and environmental assessment*. PhD Thesis. UK: Imperial College of Science, Technology and Medicine (University of London).

Slade, R., Bauen, A. & Shah, N., 2009. The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe. *Biotechnology for Biofuels*, 2, pp.15-15.

Tarkalson, D. et al., 2009. Impact of removing straw from wheat and barley fields: A literature review. *Better Crops*, 93(3), pp.17-19.

Weidema, B., 2003. *Market information in life cycle assessment*, Denmark: Danish Environmental Protection Agency.

Whitbread, A. et al., 2003. Managing crop residues, fertilizers and leaf litters to improve soil C, nutrient balances, and the grain yield of rice and wheat cropping systems in Thailand and Australia. *Agriculture, Ecosystems & Environment*, 100(2-3), pp.251-263.

Whittaker, C. et al., 2009. *The Life Cycle Analysis of Using Biomass for Heat and Electricity Production in the UK*, UK: Imperial College London. Available at: https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnxiaW9lbmVyZ3lwb3BzfGd4OjVhNDk2YzNhMTEwMjk2NWU.

Wooley, R. et al., 1999. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios*, USA: National Renewable Energy Laboratory.

WRAP, 2002. End of life vehicles. Available at: http://www.wasteonline.org.uk/resources/informationsheets/vehicle.htm#6 [Accessed February 15, 2011].